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Patents ADP number *(if you know it)*	54510003
If the applicant is a corporate body, give the country/state of its incorporation	GB
4. Title of the invention	Three Dimensional Imaging System
5. Name of your agent *(if you have one)*	Skelton, Stephen Richard
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DUPLICATE

Three-dimensional Imaging System

The current invention concerns a system for imaging simultaneously multiple layers within a three-dimensional object field and has applicability in fields including optical information storage, imaging short-timescale phenomena, microscopy, imaging three-dimensional object structures, passive ranging, wavefront analysis and millimetre wave optics.

The use of an undistorted one-dimensional amplitude grating to produce identical images of a scene in several diffraction orders is known. Most of the energy is concentrated in the zero order with most of the remaining energy being contained in the +1 and -1 orders. Phase or phase and amplitude gratings may be used to change the distribution of energy in the different diffraction orders.

It is also known that distortions of such a grating (i.e. dislocations in a direction perpendicular to the grating lines) may be used to produce phase changes in the optical system and thus shape the wavefront in the back focal plane of the system. This effect has been used to separate redundant baselines in a masked-aperture system using a dislocated grating and has formed the basis for computer generated holograms for many years (P M Blanchard, A H Greenaway, R N Anderton, R Appleby, 'Phase calibration of arrays at optical and millimetre wavelengths', J. Opt. Soc. Am. A., Vol 13, No. 7, pp1593-1600, 1996; G Tricoles, 'Computer generated holograms: an historic review', Appl. Opt., Vol 26, No. 20, pp4351-4360, 1987 and M Li, A Larsson, N Eriksson, M Hagberg, Continuous-level phase only computer generated holograms realised by dislocated binary gratings', Opt. Lett., Vol. 21, No 18, pp1516-1518, 1996).

The imaging of a three-dimensional object using a 'through-focal series' is also known. By this method a sequence of images of the object are taken with the optical system focused on different planes in the object field. An alternative approach forms simultaneously a matrix of images recorded through a matrix of lenses, each of which provides a different focus condition.

A disadvantage of the 'through-focal series' is that because the images are recorded sequentially it is ill-suited to imaging the three-dimensional structure of dynamic processes. A disadvantage of the second approach is its complex design and that the resolution obtained is

limited to the resolution delivered by the individual lenses in the array, the diameter of each of which (thus image resolution) is constrained by the space into which the array may be packed.

The storage of data in three dimensional, optically readable, storage medium is also known (S Jutamulia and G M Stori, 'Three-Dimensional Optical Digital Memory', Optoelectronics - Devices and Technologies Vol 10, No. 3, pp343-360, 1995 and K Kobayashi and S S Kano, 'Multi-Layered Optical Storage with Nonlinear Read/Write', Optical Review, Vol 2, No 1, pp20-23, 1995). These papers review the media and architecture for various three dimensional optical memories.

According to this invention an apparatus for producing simultaneously in a common plane, spatially-separated images of an object field comprises:

a diffraction grating capable of producing an image associated with each diffraction order and being substantially quadratically distorted so as to cause the images to be formed under various focus conditions;

means for detecting two or more of the spatially-separated images

and imaging means, capable of directing radiation from the grating to the detecting means;

wherein the imaging means, diffraction grating and detecting means are arranged on an optical axis which intersects the object field and the diffraction grating is located in a suitable grating plane.

The object field may be self luminous, naturally illuminated or artificially illuminated.

The invention utilises a single lens or multiple lens system with a distorted diffraction grating to produce simultaneously, in a side-by-side arrangement, a set of images of the object field in which each image in the set can correspond to an image of the object field recorded under different focus conditions but in which the full diameter of the lens system is exploited in each

image in the set. For each image in the set, the resolution, magnification and depth of focus is that which would have been obtained if a through focal series had been produced by varying only the focal length of the lens system.

Thus images of loci of different depth within the object field can be produced simultaneously on a single plane. This would allow simultaneous reading of optical data stored in different layers within a suitable storage medium.

The grating used can be a single distorted diffraction grating or a series of such gratings. The gratings used may be produced by computer-generated (digitised in space and/or in amplitude) or by analogue (e.g. interferometric) means, may be amplitude-only, phase-only or amplitude and phase and may be reflective or transmissive in nature.

In the following descriptions detector means a detection means comprising a spatially-resolving system such as a pixellated array of detector elements such as a charge coupled device (CCD). For applications where detection of the presence or absence of unresolved targets is required, the detector may comprise suitably-positioned, isolated detector elements.

The invention will now be described with reference to the following figures in which:

figure 1 shows schematically suitable grating planes, by way of illustration only.

figure 2(a) shows schematically a conventional, undistorted, amplitude-only diffraction grating used in an imaging system and figure 2(b) shows the zero, +1 and -1 diffraction order images produced when such a grating is inserted in a suitable grating plane of an imaging system;

figures 3a and 3b illustrate respectively an undistorted grating and the distortion of a grating by a fixed amount, Δ;

figure 4 shows schematically a simple imaging system of the current invention;

figure 5 shows two computer generated amplitude gratings;

figure 6 shows computer simulations of images of a point source, formed in the +1, 0 and -1 diffraction orders by the current invention;

figure 7 shows experimental measurements of the images of a resolution target formed in the +1, 0 and -1 diffraction orders by the current invention;

figure 8(a) shows crossed amplitude gratings, figure 8(b) shows the defocus states of the corresponding diffraction orders and figure 8(c) shows a computer simulation of the image of a point source through the grating structure of figure 8(a);

figure 9 shows experimental images of a resolution target obtained using crossed amplitude gratings;

figure 10 shows schematically a simple imaging system of the current invention used to produce in-focus images of different object planes at a single detector plane;

figure 11 shows images of an extended pinhole obtained by experiment using a quadratically distorted amplitude grating;

figure 12 shows schematically the apparatus used to record the experimental data shown in figure 13;

figure 13 shows simultaneous side-by-side images of 3 objects located in different object planes and

figure 14 shows how the invention may be adapted for reading of data stored in a three dimensional optical storage medium.

Although the following examples relate to application of the invention in the field of optics, this should not be seen as limiting as the general principles of the invention are applicable to other wavelengths of electromagnetic radiation.

Grating Location

In a system in which converging and/or diverging beams exist, a suitable grating plane would be any plane that is normal to the optical axis and close to a lens other than a lens positioned in the image or object field, for example plane P1 in figure 1a. In a system where a collimated beam is produced, a suitable grating plane would be any plane that is normal to the optical axis of the system and in the region in which the beam is collimated, for example anywhere between planes P1 and P2 in figure 1b, or a plane described as a suitable grating plane for a system with converging or diverging beams.

Grating Design

The design of distorted gratings which might typically be used in the current invention will first be described.

A standard one-dimensional diffraction grating consists of alternate regularly spaced strips of different transmissivity, reflectivity or optical thickness. When the grating is used within an imaging system, multiple diffraction orders appear in the image plane in addition to the unscattered zero order. Each diffraction order contains the same information about the object field as the zero order, though with different levels of intensity dependent on details of the grating construction. Figure 2 shows, as an example, a one-dimensional amplitude grating and the images of a point object formed in the –1, 0 and + 1 diffraction orders.

If the grating geometry is distorted locally, by a displacement of the strips in a direction perpendicular to their long axis, a phase shift is introduced in the wavefront scattered from the distorted region, the level of which is dependent on the amount of local distortion of the grating relative to its undistorted form. The level of local phase shift is related to the distortion of the grating through equation 1,

$$\phi = \frac{2\pi m\Delta}{d} \qquad \text{Equation 1}$$

where d is the grating period, m is the diffraction order into which the wavefront is scattered and Δ is the distortion of the grating strips relative to their undistorted position, as shown in figure 3. Such a distortion of the grating produces phase shifts of equal magnitude but opposite

sign in the wavefronts scattered into +1 and −1 diffraction orders and leaves the unscattered wavefront in the zero order unaltered.

It is important to note that this technique allows continuous phase values to be encoded using a binary (two level) grating, although the invention can also be applied to multiple or continuous level gratings.

For applications using computer-generated holograms, the distorted grating can be designed by dividing the grating area into a number of cells, which can be of any space-filling shape, and calculating the degree of distortion to be applied to the grating for each cell individually. Alternatively the distortion can be applied to the grating as a whole leading to continuously distorted strips. Both of these approaches can be implemented using computer design followed by grating fabrication or by using an electrically addressed liquid crystal or other electro-optic device.

For non-digital production methods an alternative technique is to record holographically the distorted fringe pattern into an optically sensitive medium, or to use an optically programmable liquid crystal device to allow the grating to be changed in real-time.

The above descriptions refer to arbitrary distortions that could be used to generate arbitrary phase changes on the wavefront scattered into a selected diffraction order.

Below are described the grating distortions required to produce the defocus effects required for implementation of this invention.

<u>Defocus Gratings</u>

A defocused optical system has a phase shift which, compared to an in-focus image, can be represented by a quadratic function of the distance from the optical axis and measured relative to the Gaussian reference sphere (e.g. section 5.1, Principles of Optics, Born & Wolf, Pergammon, Edition 6, Oxford, 1980). This invention relates to a diffraction grating distorted as a quadratic function of distance from the optical axis of the system according to,

$$\Delta(x,y) = \frac{{}_0C_{20}d}{\lambda r^2}(x^2 + y^2)$$ Equation 2

where $\Delta(x,y)$ is a distortion in a direction perpendicular to the grating lines (figure 3), x and y are Cartesian co-ordinates relative to an origin on the optical axis in the plane of the grating, d is the grating period, λ is the optical wavelength, ${}_0C_{20}$ is the degree of defocus introduced into the image formed in the +1 diffraction order (${}_0C_{20}\geq0$) and r is the radius of the grating aperture which is centred on the optical axis. In equation 2 a circular aperture has been assumed, but the invention can be applied to an aperture of any shape. ${}_0C_{20}$ is the wavefront coefficient of defocus of the grating (the traditional defocus aberration constant equivalent to the pathlength difference introduced at the edge of the aperture between, in this case, the wavefront scattered into the +1 diffraction order and the Gaussian reference surface for that diffraction order {e.g. section15-5, Geometrical and Physical Optics, R S Longhurst, Longman, Edition 3, London, 1973}). The phase change imposed on the wavefronts scattered into the various diffraction orders can be calculated by combining equation 1 and equation 2 to give,

$$\phi(x,y) = m\frac{2\pi\,{}_0C_{20}}{\lambda r^2}(x^2 + y^2)$$ Equation 3

This quadratic phase shift, introduced by the grating, leads to a defocus of all diffraction orders other than the zero order. The magnitude and sign of the defocus is dependent on the diffraction order (m). Thus a series of images of the object field with differing defocus conditions is produced simultaneously and side-by-side on the detector in the different diffraction orders.

The principle of the invention can be demonstrated with reference to the -1, 0 and +1 diffraction orders. Referring to figure 4, the defocusing effect of a quadratically distorted grating can be demonstrated using an optical system (1), designed and arranged to image an object (2) on the optical axis (3) onto detector plane B at the normal focal plane of the optical system.

A quadratically distorted diffraction grating (4) which is added to the optical system (1) produces two additional images of the object (2) in plane B in its +1 and -1 diffraction orders. In the normal focal plane B the zero order image remains in focus, whilst the images in the +1

and −1 diffraction orders undergo defocus of equal magnitude but opposite sign. If the detector is moved along the optical axis either side of plane B, a plane can be reached where the physical defocus cancels out the defocus introduced by the grating into the diffraction orders. In this way the images in the +1 and −1 diffraction orders can be brought in to focus (planes A and C).

The separation δ_i of the image planes A, B and C is determined by the grating distortion, the radius of the grating aperture and the optical system through,

$$\delta_i \approx \frac{2v^2 m\ {}_0C_{20}}{2vm\ {}_0C_{20} + r^2} \qquad \text{Equation 4}$$

where r is the grating aperture radius, v is the distance from the normal image plane (B) to the secondary principle plane of the optical system, and the approximation v >> r (v is much greater than r) has been made. Terms of higher order in v and r can be used in cases where v is not much greater than r. Note that if a grating is designed with defocus represented by ${}_0C_{20} =$ $n\lambda$, then the +1 diffraction order undergoes a defocus equivalent to $n\lambda$, the −1 diffraction order will undergo a defocus equivalent to $-n\lambda$ and, through equation 4, planes A and C will be located either side of and at different distances from plane B.

In the case where $2vm_0C_{20} << r^2$, equation 4 can be approximated by,

$$\delta_i \approx 2m\left(\frac{v}{r}\right)^2 {}_0C_{20} \qquad \text{Equation 5}$$

and planes A and C are symmetrically placed about plane B.

Equation 4 can be rearranged in terms of the grating defocus (${}_0C_{20}$) needed to generate the required image plane separation (δ_i) between in-focus images in the zero and +1 diffraction orders (m=1),

$${}_0C_{20} = \frac{r^2\delta_i}{2v(v-\delta_i)} \qquad \text{Equation 6}$$

Figures 5(a) and 5(b) each show examples of gratings with spherical apertures and distorted as a quadratic function of distance from the centre, to give different levels of defocus, for figure 5(a), ${}_0C_{20}=\lambda$ and for figure 5(b), ${}_0C_{20}=2\lambda$. These represent two examples of many possible grating structures and were designed by computer as binary amplitude gratings using a square design cell.

The defocusing property of these gratings has been verified with computer simulations and experimentally as will be described later.

Imaging a single object through a one-dimensional defocusing grating - Computer Simulations
Computer simulations were performed using software written in Fortran using a Fast Fourier Transform (FFT) routine [Subroutine *fourn* from 'Numerical recipes in Fortran', W H Press, S A Teukolsky, W T Vetterling, B P Flannery, Cambridge University Press, 1992]. Images were calculated by multiplying the FFT of the object by the optical transfer function of the grating, followed by an inverse FFT to generate the image. The optical transfer function of the grating was calculated from the autocorrelation of the grating, obtained via a double FFT technique using the Wiener-Khintchine Theorem [Fourier Optics : An Introduction, E G Steward, 2nd edition, p95, J Wiley & Sons.]. This approach represents a simulation of incoherent imaging.

Figure 6 shows simulated images of a point source through a distorted amplitude grating designed with ${}_0C_{20} = \lambda$ (figure 5a), with the detector placed at planes A, B and C (figure 4). Using an amplitude grating, the intensities of the first order diffraction spots would, in practice, be lower than that of the zero order. In this figure the intensities of the +1 and −1 diffraction orders have been increased to that of the zero order to aid observation. With the detector in plane B, the zero order is in focus and the +1 and −1 diffraction orders have defocuses of $+1\lambda$ and -1λ respectively. By moving the detector either side of this plane, the +1 and −1 diffraction orders can be brought into focus. This demonstrates that the mask is generating a true defocus.

Imaging a single object through a one dimensional defocusing grating – Experimental Results
In order to verify the computer simulations, a grating was fabricated by photographically reducing an enlarged black and white picture of the appropriate pattern on to a 35mm slide. This provided a grating with a circular aperture of diameter 1cm, ${}_0C_{20}=\lambda$ and a grating period of

400×10^{-6}m (400μm). The optical system comprised two lenses with focal lengths of 50cm and 100cm, separated by 5cm. The object, a standard resolution target, was placed one focal length (50cm) in front of the first lens and the detector was placed one focal length (100cm) behind the second lens. A white light source was used to illuminate the object in transmission and the grating was placed between the two lenses in the region where the light was collimated. A filter with a bandpass of 10nm, centred at 650nm, was placed in front of the CCD detector used to record the image.

These parameters lead to an axial focal shift of +4.9cm and −5.5cm in the +1 and −1 diffraction orders respectively (equation 4). Figure 7 shows the images obtained upon location of the detector at positions corresponding to planes A, B and C of figure 4. The figure shows the raw images captured by the detector and the same images after processing to increase the intensities of the +1 and −1 diffraction orders (normalised), to aid observation. It can be seen that the −1, 0 and +1 diffraction orders are brought into focus as the detector is scanned along the optical axis of the system. At these positions, the physical defocus is cancelling out the wavefront deformations introduced by the gratings, that is the grating is introducing the quadratic variation of phase (defocus) predicted.

Imaging a single object through a two-dimensional defocus grating

The techniques described so far can be extended by using two-dimensional or multiple crossed one-dimensional gratings. If two gratings are crossed at right angles, the central nine diffraction orders can be usefully used. If the defocuses ($_0C_{20}$) of the two crossed grating are chosen to be $a\lambda$ and $b\lambda$ then, for $|a-b| \neq a \neq b$, the nine images of the scene that are formed in parallel correspond to nine different defocus conditions. Figure 8a shows an example of two crossed gratings having defocuses of $_0C_{20}=1\lambda$ and $_0C_{20}=1.5\lambda$, figure 8b shows the relative defocuses of the central nine diffraction orders and figure 8c shows a computer simulation of the image of a point source through the gratings (normalised). The image of the object in each diffraction order can be brought separately into focus by movement of the detector along the axis.
The crossed grating technique has been tested experimentally using the arrangement previously described and the crossed grating structure illustrated in figure 8a. The experimental results in figure 9 show a selection of the nine images, brought into focus by moving the detector along

the optical axis. The full range of motion of the detector between the two extremes in figure 9 was approximately 20cm.

<u>Imaging multiple object planes through a one-dimensional defocus grating</u>

The function of the defocus grating can be considered in a different way. Referring to figure 10, if the detector is placed at image plane B, then the three images formed correspond to in-focus images of three different object planes 5, 6 and 7. The zero order will be the sum of the out-of-focus images of objects 5 and 7 and an in-focus image of object 6. If the degree of defocus is sufficient, a good image of object 6 will result. Similarly, objects 5 and 7 are discernible in the +1 and -1 diffraction orders. The grating therefore generates, side-by-side, simultaneous images of three different object planes at a single detector plane. The separation (δ_o) of the object planes imaged in plane B is determined by the grating distortion, the radius of the grating aperture and the optical system through,

$$\delta_o \approx \frac{2u^2 m\ {}_0C_{20}}{2um\ {}_0C_{20} + r^2} \qquad \text{Equation 7}$$

where ${}_0C_{20}$ is the wavefront coefficient of defocus of the grating for the +1 diffraction order, r is the grating aperture radius, m is the diffraction order, u is the distance from the central object plane to the primary principle plane of the optical system, and the approximation u >> r has been made.

The resolution in depth, in terms of the minimum separation of planes in the object field that can be individually imaged, is dependent on the depth of focus of the optical system being used
The image quality obtained when using a distorted diffraction grating to image multiple planes within the object field will be the same as if a 'through focal series' were obtained by adjusting the optical system to adjust its focus to image the same planes.
The fact that different object planes are imaged into different diffraction orders was first observed using a fixed detector and a single moveable object. Figure 11 shows images obtained on locating a 400×10^{-6}m (400μm) diameter pinhole at positions corresponding to object planes 5, 6 and 7 of figure 10. The optical system comprised of two lenses with a focal lengths of

50cm and 100cm, separated by 5cm, a CCD detector fixed at 100cm from the second lens (plane B) and a grating with an aperture diameter of 1cm, ${}_0C_{20}=\lambda$ and a period of 400×10^{-6}m (400µm). Object plane 6 corresponded to a plane 50cm from the first lens and the grating parameters produced in-focus images in its −1 and +1 diffraction orders of object planes displaced by +1.3cm and −1.3cm relative to plane 6.

In order to demonstrate the simultaneous imaging of three object planes, the same optical system was used but with a grating of ${}_0C_{20}=2\lambda$. Plane 6 corresponded to a plane 50cm from the first lens and planes 5 and 7 corresponded to object planes displaced by +2.5cm and −2.7cm relative to plane 6. A 400×10^{-6}m (400µm) pinhole, a piece of lens tissue and vertical wire of diameter 175µm were placed at object planes 5, 6 and 7 respectively, all on optical axis 3, as shown schematically in figure 12. A white light source (not shown) was used to illuminate the objects in transmission, with the pinhole at plane 5 acting to apodise the images such that the image sizes were less than the separation of diffraction orders on detector 8. Due to this illumination scheme the pinhole appears as an illuminated circle, whilst the other objects appear as dark shadows on an illuminated background. A filter 9 centred at 650nm, with a bandpass of 10nm was located over the detector aperture. The detector was also moved along the optical axis to the positions where the diffraction orders imaged different objects, corresponding to planes A and C in figure 4. These positions were 9.4cm and −11.6cm from the image plane B.

Figure 13 shows the images recorded on the detector at planes A, B and C of figure 12. At position B, the zero order images object plane 6 (the lens tissue), the −1 diffraction order images object plane 7 (the wire) and the +1 diffraction order images object plane 5 (the pinhole) of figure 12. These images demonstrate experimentally that three object planes can be imaged simultaneously and side-by-side on a single detector. With two crossed gratings it is possible to image simultaneously nine object planes side-by-side on a single detector.

Phase Gratings

If an amplitude grating is used as a defocusing element, the zero order is always brighter than the +1, -1 and higher diffraction orders. The distribution of energy can be adjusted using a phase grating with two phase levels. For example, a phase step of π radians can completely

eliminate the zero order, whilst putting more power into the +1 and −1 orders, or the phase step can be adjusted to place equal power into the 0, +1 and −1 orders. With crossed gratings the use of more phase steps or combined amplitude and phase gratings can be used to adjust the intensities of the multiple diffraction orders.

Polarisation-Sensitive Gratings

A distorted grating that is fabricated such that it operates only on one polarisation state of the incident wavefront will produce polarised, defocused images of the target in the +1 and −1 diffraction orders and an unpolarised image in the zero order. If a second grating, that operates only on the orthogonal polarisation, is crossed with the first grating then two further diffraction orders will be produced, polarised in the orthogonal sense and displaced from the set produced by the first grating. Because the gratings are polarisation sensitive there is no crosstalk between the gratings and thus no diffraction orders are produced other than would be produced by each grating acting alone. If the system is required for polarimetric studies the defocus can be chosen to be the same for each polarisation state. Because the images are produced simultaneously the system is suitable for polarimetric studies of dynamically-changing scenes.

Three Dimensional Optical Data Storage.

Referring to figure 14, apparatus of the invention, adapted for reading data stored in a three dimensional optical storage medium 11 is generally designated 10. The storage medium 11 comprises discrete optically readable planes 5, 6, 7 having individual data storage bits (not shown) located thereon and is illuminated by means not shown. The data storage bits are imaged simultaneously at detectors 12. Detectors 12 are capable of producing a signal dependent on the state of the storage bit (i.e. whether a logical '0' or '1' is stored and could be a photodiode or a photo transistor.

In order to facilitate interrogation of different data bits within each plane, the apparatus includes means (not shown) for effecting relative movement, in a direction perpendicular to optical axis 3, between the storage medium 8 and the rest of the apparatus. Such means would typically comprise an electromechanical arrangement known to a person skilled in the art.

Claims

1. An apparatus for producing simultaneously in a common plane, spatially-separated images of an object field comprising:

a diffraction grating capable of producing an image associated with each diffraction order and being substantially quadratically distorted so as to cause the images to be formed under various focus conditions;

means for detecting two or more of the spatially-separated images

and imaging means, capable of directing radiation from the grating to the detecting means;

wherein the imaging means, diffraction grating and detecting means are arranged on an optical axis which intersects the object field and the diffraction grating is located in a suitable grating plane.

2. An apparatus according to claim 1 whereby the imaging means comprises a lens system with two or more optical elements

3. An apparatus according to claims 1 or 2 whereby the diffraction grating comprises a set of two or more crossed one-dimensional diffraction gratings

4. An apparatus according to claims 1 or 2 whereby the diffraction grating comprises a set of two or more one-dimensional diffraction gratings designed such that the various diffraction orders are spatially separated.

5. An apparatus according to claims 1 or 2 whereby the diffraction grating comprises a two-dimensional diffraction grating.

6. An apparatus according to claims 1 to 5 whereby the diffraction grating is an amplitude-only diffraction grating.

7. An apparatus according to claims 1 to 5 whereby the diffraction grating is a phase-only diffraction grating.

8. An apparatus according to claims 1 to 5 whereby the diffraction grating is a phase and amplitude diffraction grating.

9. An apparatus according to any preceding claim whereby the diffraction grating is polarisation sensitive.

10. An apparatus according to claims 1 to 8 whereby the diffraction grating comprises two gratings sensitive to different polarisations and arranged such that the diffraction orders produced by said gratings are spatially separated.

11. An apparatus according to any preceding claim whereby the diffraction grating is a programmable grating.

12. An apparatus according to any preceding claim whereby the diffraction grating is a reflective grating.

13. An apparatus according to claims 1 - 11 whereby the grating is a transmissive grating.

14. An apparatus according to any preceding claim whereby the grating is a two-level (binary) structure.

15. An apparatus according to claims 1 to 13 whereby the grating is a multi-level (digitised) structure.

16. An apparatus according to claims 1 to 13 whereby the grating is a continuous-level (analogue) structure.

16

17. An apparatus according to any preceding claim for producing in-focus images on a single plane from a plurality of object planes on the optical axis.

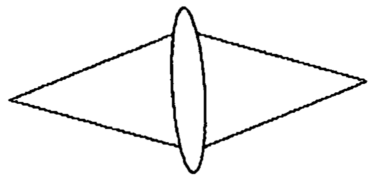
18. An apparatus according to any preceding claim whereby each object field exists in one of two states and in which the detector means is capable of distinguishing between said states.

19. An apparatus according to any preceding claim adapted for reading data from a three dimensional optical storage medium wherein the detecting means is capable of producing a signal dependent on the state of individual data storage bits within the medium.

Abstract

A three dimensional imaging system is described which exploits the defocusing of non-zero diffraction order images caused by the quadratic distortion of a diffraction grating 4. An optical system 1 is used such that objects 5, 6 and 7, located at different distances from grating 4, are imaged simultaneously and spatially separated on a single plane B.

i)



ii)

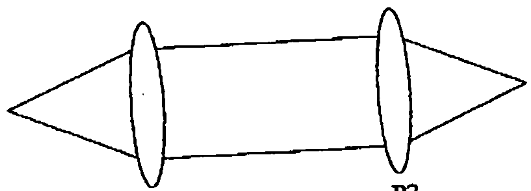


Figure 1

(a) (b)

Figure 2

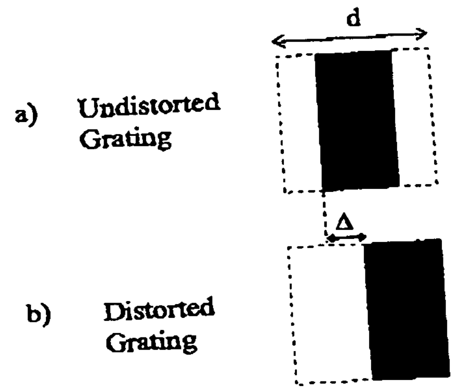


Figure 3

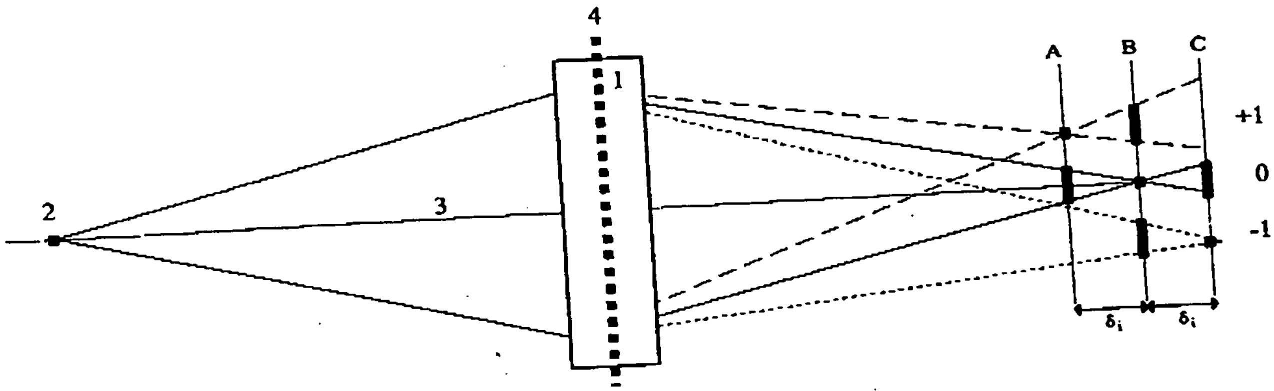
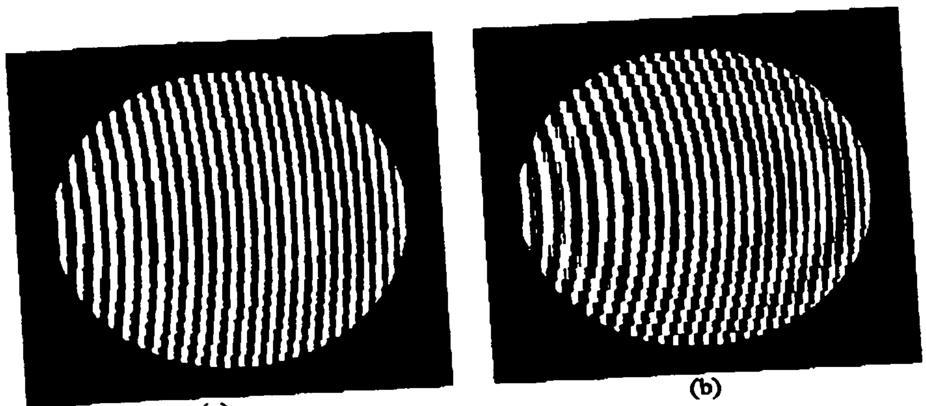


Figure 4



(a) (b)

Figure 5

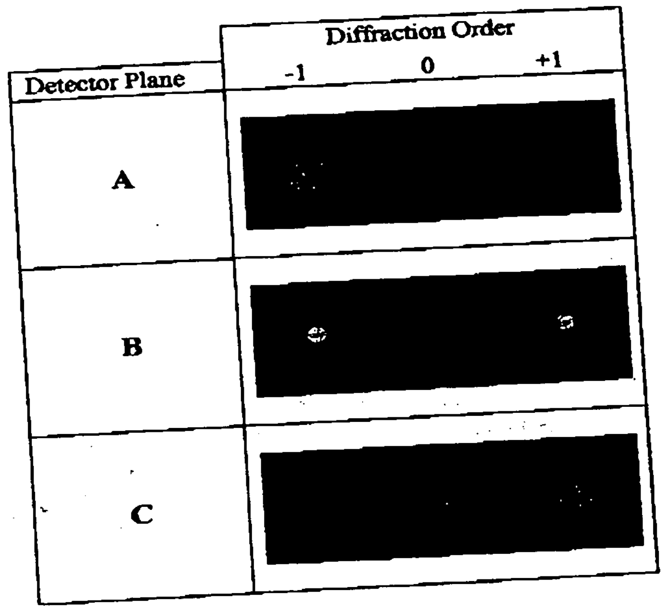


Figure 6

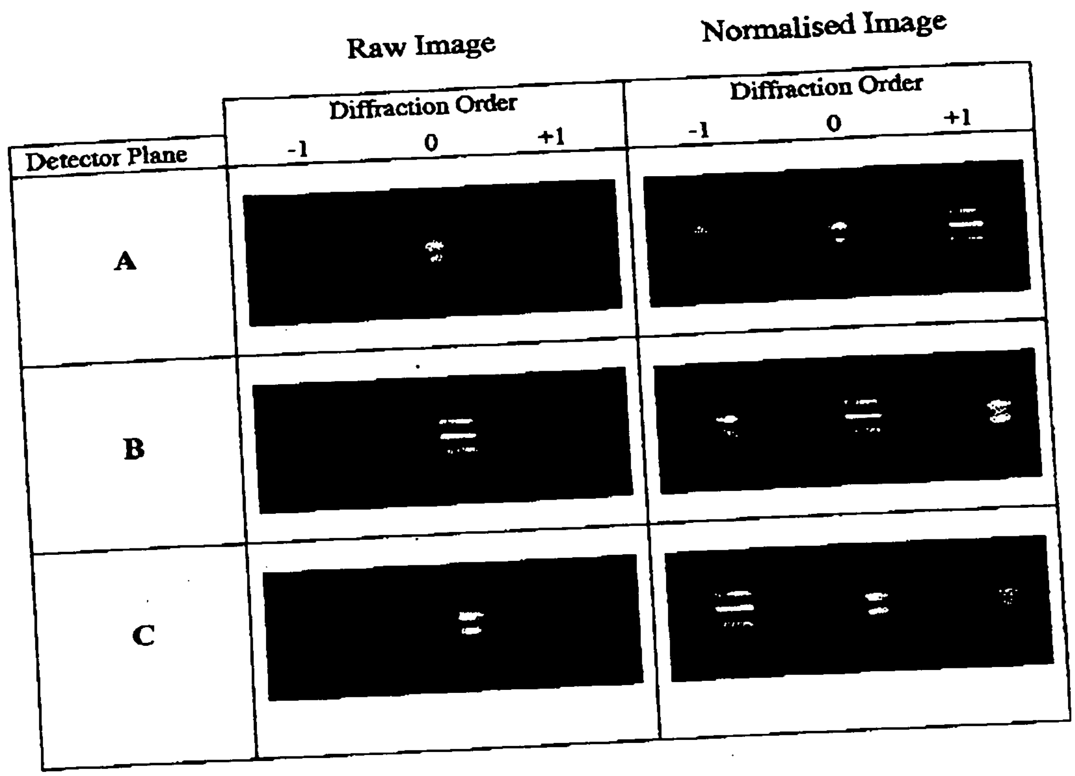
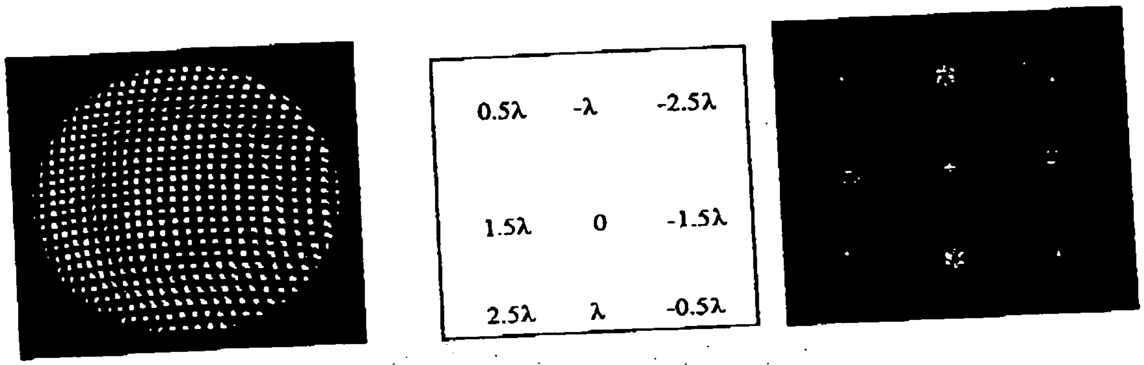

Raw Image
Normalised Image
Diffraction Order
-1
0
+1
Diffraction Order
-1
0
+1
Detector Plane
A
B
C

Figure 7



(a) (b) (c)

Figure 8

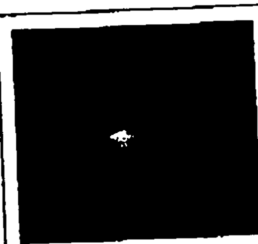
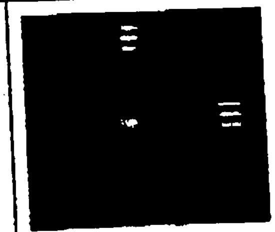
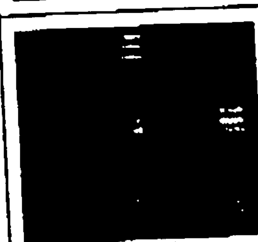
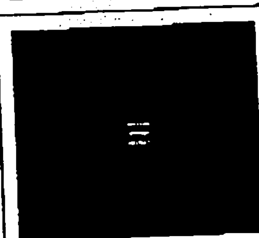
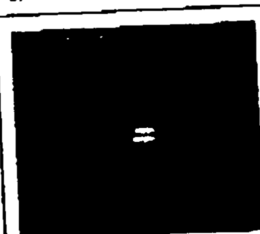
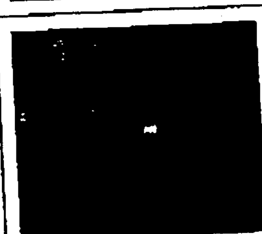
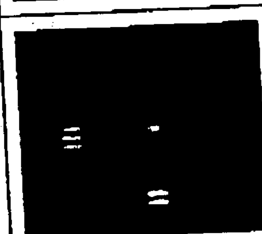
Camera Position Expressed as Defocus	Raw Image	Normalised Image
-1.5λ		
-λ		
0		
λ		
1.5λ		
2.5λ		

Figure 9

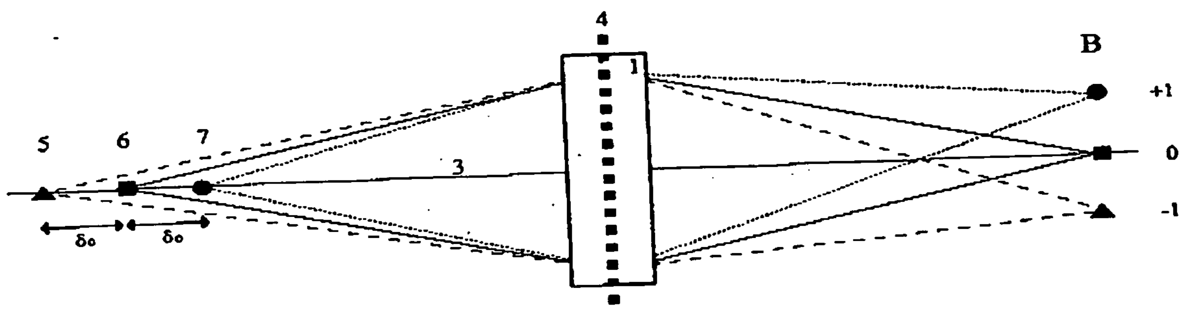


Figure 10

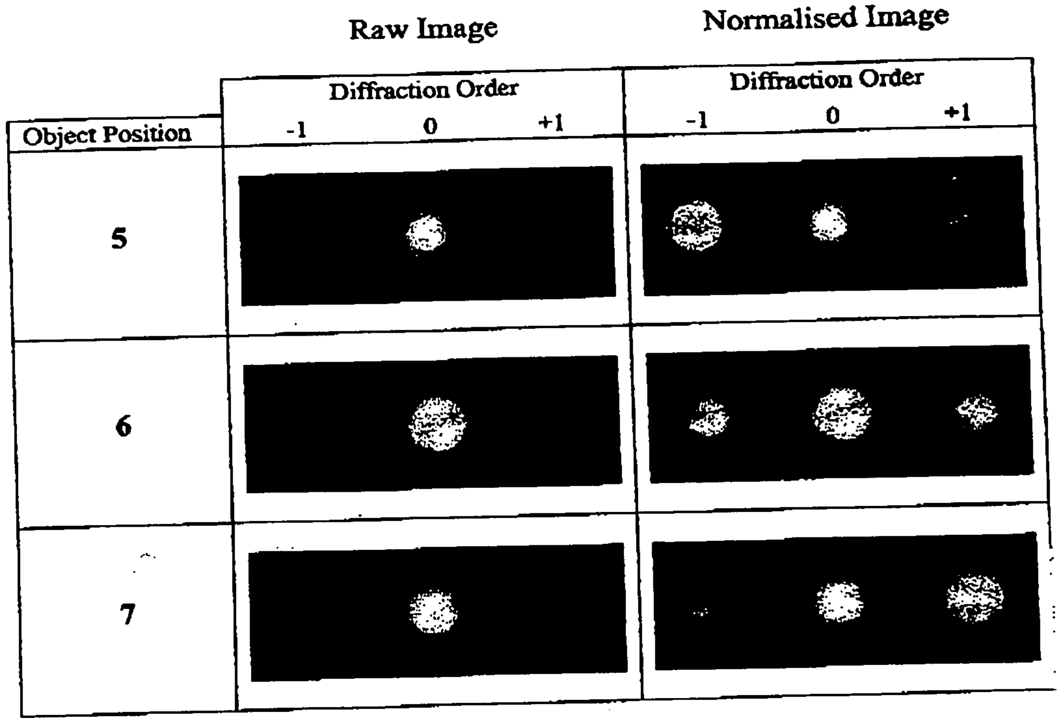

Raw Image
Normalised Image
Diffraction Order
Diffraction Order
Object Position
-1
0
+1
-1
0
+1
5
6
7

Figure 11

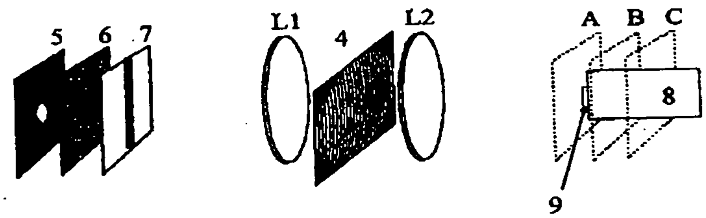


Figure 12

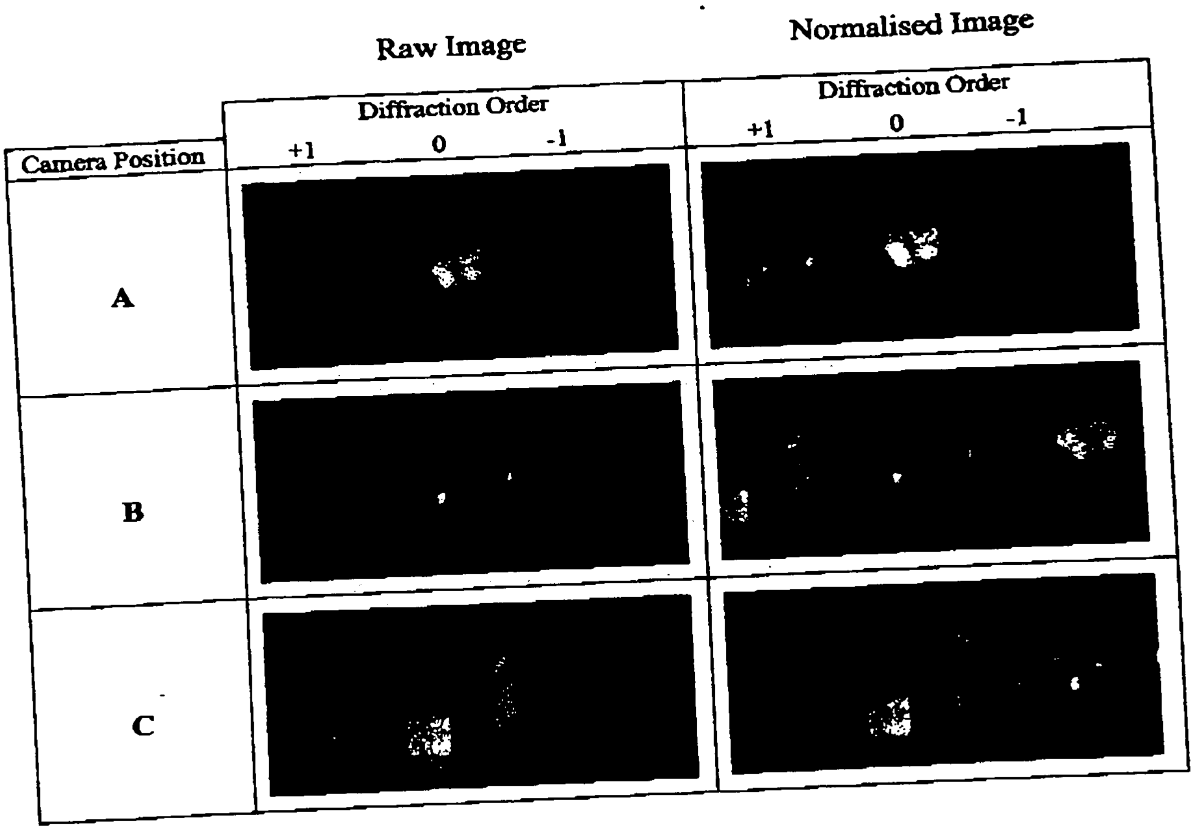

Raw Image
Normalised Image
Diffraction Order
Diffraction Order
Camera Position
+1
0
-1
+1
0
-1
A
B
C

Figure 13

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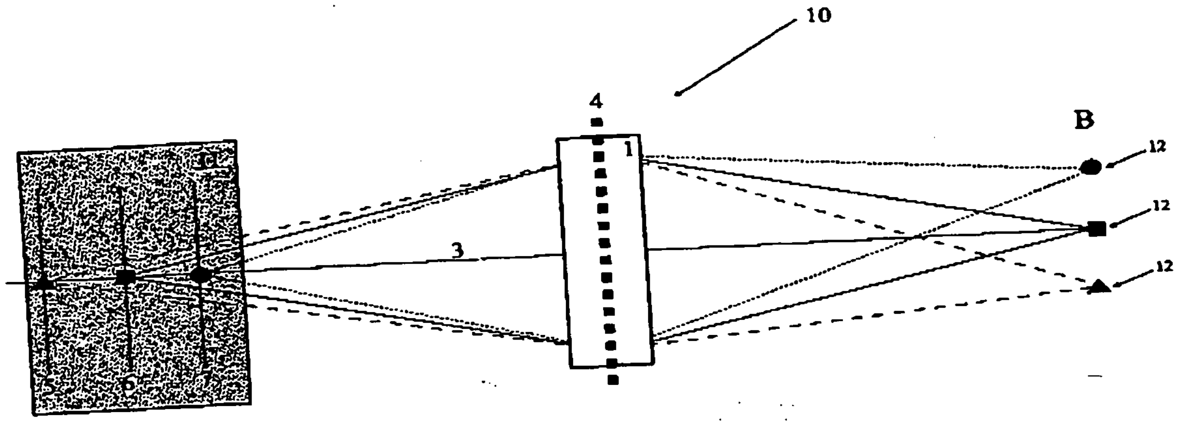

Figure 14

PCT/GB 99/00658
5/3/99
DERA

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